

Single spin asymmetry in πp Drell-Yan process

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Abstract

We study the single spin asymmetries for the $\pi p^\uparrow \rightarrow \mu^+ \mu^- X$ process. We consider the asymmetries contributed by the coupling of the Boer-Mulders function with the transversity distribution and the pretzelosity distribution, characterized by the $\sin(\phi + \phi_S)$ and $\sin(3\phi - \phi_S)$ azimuthal angular dependence, respectively. We estimate the magnitude of these asymmetries at COMPASS by using proper weighting functions. We find that the $\sin(\phi + \phi_S)$ asymmetry is of the size of a few percent and can be measured through the experiment. The $\sin(3\phi - \phi_S)$ asymmetry is smaller than the $\sin(\phi + \phi_S)$ asymmetry. After a cut on q_T , we succeed in enhancing the asymmetry.

Key words: Drell-Yan process, single spin asymmetry, transverse momentum dependent distribution, pretzelosity

PACS: 12.38.Bx, 12.39.Ki, 13.75.Gx, 13.85.Qk

1 introduction

The single transverse spin asymmetries (SSAs) appearing in various high energy scattering processes [1,2] are among the most interesting issues of QCD spin physics. Substantial SSAs in semi-inclusive deeply inelastic scattering (SIDIS) [3,4,5,6,7,8,9], with one colliding nucleon transversely polarized, have

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been measured by several experiments. These asymmetries, together with the large asymmetries measured in $pp^\uparrow \rightarrow \pi X$ process [10,11,12], cannot be explained by the leading-twist collinear picture of QCD [13]. It is found that the time-reversal-odd (T -odd) distribution functions or fragmentation functions play essential roles for these asymmetries. Of particular interests, are the leading-twist T -odd transverse momentum dependent (TMD) distribution functions, such as the Sivers function [14,15] and the Boer-Mulders function [16]. They arise from the correlation between the nucleon/quark transverse spin and the quark transverse momentum, and can provide necessary interference of amplitudes with different helicities and phases for SSAs in the leading twist. Hence the study on these TMD distributions and associated asymmetries can provide new insights into QCD dynamics and nucleon structure [17,18,19,20].

In this Letter we will explore the leading-twist SSAs in πp^\uparrow Drell-Yan process where the proton is transversely polarized. In the TMD factorization picture, there are two mechanisms for the SSAs in πp^\uparrow Drell-Yan process at the leading twist. One is the Sivers effect from the transversely polarized proton, characterized by the $\sin(\phi - \phi_S)$ angular dependence, where ϕ and ϕ_S are the azimuthal angles of the lepton pair and the proton transverse spin, respectively. The other one is the Boer-Mulders effect from the π meson. The studies on the former one were carried out in Refs. [21,22], which revealed the possibility to test the sign reversal of T -odd distributions between SIDIS and Drell-Yan process, a crucial prediction of QCD dynamics. Here we will explore the SSAs in πp^\uparrow Drell-Yan process from the Boer-Mulders effect of the π meson, since they have not been studied in detail phenomenologically. As Boer-Mulders function is chiral-odd, it can only convolute with another chiral-odd object constrained by helicity conservation in hard partonic scattering process. For a transversely polarized proton the leading-twist chiral-odd structure is manifested by the transversity distribution and the pretzelosity distribution, of which the combinations with the Boer-Mulders function yield the $\sin(\phi + \phi_S)$ and $\sin(3\phi - \phi_S)$ azimuthal asymmetries, respectively. The transversity distribution, usually denoted as $h_1(x)$, can be interpreted as the difference between the densities of quarks with transverse (Pauli-Lubanski) polarization parallel or anti-parallel to the transverse polarization of the nucleon. Due to its chiral-odd nature, transversity cannot be measured in inclusive DIS process. Other than the double transversely polarized Drell-Yan process, it was realized that transversity can also be accessed in semi-inclusive DIS through the Collins effect [23], and in Drell-Yan process through the Boer-Mulders effect [24]. The pretzelosity distribution, denoted as $h_{1T}^\perp(x, \mathbf{p}_T^2)$, provides supplementary chiral-odd structure of transversely polarized nucleon, especially when the parton transverse momentum is probed. Studies on pretzelosity can be found in Refs. [25,26]. Further interest in pretzelosity relies on the observation that it provides the information of the quark orbital angular momentum inside the nucleon [26] in a model dependent manner. Besides the SIDIS process,

pretzelosity can also be accessed in single polarized Drell-Yan process.

In the present work, we study the SSAs in πp^\uparrow Drell-Yan process contributed by the coupling of the Boer-Mulders function of the pion with the transversity and pretzelosity of the nucleon, respectively. The hadron program by the COMPASS collaboration will start at CERN, in which a π^- beam colliding with proton target is going to be available. In this work, we estimate the $\sin(\phi + \phi_S)$ and $\sin(3\phi - \phi_S)$ azimuthal asymmetries at COMPASS, not only for the $\pi^- p^\uparrow$ process, but also for the $\pi^+ p^\uparrow$ process. We show that πp^\uparrow Drell-Yan process could be applied to probe the chiral-odd structure of the transversely polarized nucleon in the leading twist.

2 Single spin asymmetry in Drell-Yan process

For a general Drell-Yan process with one of the beam transversely polarized, i.e., $h_1 h_2^\uparrow \rightarrow \ell^+ \ell^- X$, the single spin asymmetry is simply defined as

$$A_{UT} = \frac{d\sigma^{h_1 h_2^\uparrow \rightarrow \ell^+ \ell^- X} - d\sigma^{h_1 h_2^\downarrow \rightarrow \ell^+ \ell^- X}}{d\sigma^{h_1 h_2^\uparrow \rightarrow \ell^+ \ell^- X} + d\sigma^{h_1 h_2^\downarrow \rightarrow \ell^+ \ell^- X}} \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}. \quad (1)$$

Here we treat the process in the parton model and only consider the leading order approximation via a single photon transfer, i.e., $q\bar{q} \rightarrow \gamma^* \rightarrow \ell^+ \ell^-$. We denote the momenta of the hadrons, the annihilating partons, and the produced lepton pairs as P_i , p_i and k_i ($i = 1, 2$), respectively. Then the momentum transfer gives the invariant mass of the lepton pair

$$q^2 = (p_1 + p_2)^2 = (k_1 + k_2)^2 = M^2. \quad (2)$$

Now we work in the center of mass frame of two hadrons, and parameterize the four-momentum of the photon as $q = (q_0, \mathbf{q}_T, q_L)$. At extremely high energies, if we assume that the longitudinal component is dominant and neglect all the mass effects and the transverse momentum, we can define the following variables,

$$x_1 = \frac{q^2}{2P_1 \cdot q} \approx \frac{q_0 + q_L}{\sqrt{s}}, \quad x_2 = \frac{q^2}{2P_2 \cdot q} \approx \frac{q_0 - q_L}{\sqrt{s}}, \\ \tau = \frac{M^2}{s}, \quad x_F = x_1 - x_2 \approx \frac{2q_L}{\sqrt{s}}. \quad (3)$$

Then we can build up the relation

$$\begin{aligned}
x_1 &= \frac{1}{2}(x_F + \sqrt{x_F^2 + 4\tau}), \\
x_2 &= \frac{1}{2}(-x_F + \sqrt{x_F^2 + 4\tau}).
\end{aligned} \tag{4}$$

The direction of the detected lepton pair can be described by the solid angle (θ, ϕ) , which is frame dependent. In our Letter, we will select the Collins-Soper frame [27]. The convention for the definition of the azimuthal angles of the lepton pair and proton transverse spin in our Letter is the same as that used in Refs. [24,28], but different with that in Ref. [29], although we can easily demonstrate that they are equivalent by a simple transformation.

Our aim is to explore the transversity and pretzelosity through SSA in πp^\uparrow Drell-Yan process, so we write down the cross-section [24,28,29] only with the terms we are interested in:

$$\begin{aligned}
\frac{d\sigma}{d\Omega dx_1 dx_2 d^2\mathbf{q}_T} &= \frac{\alpha^2}{3q^2} \{ A(y) \mathcal{F}[\bar{f}_1 f_1] \\
&- |\mathbf{S}_{2T}| [B(y) \sin(\phi + \phi_{S_2}) \times \mathcal{F}[\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_{1T}}{M_1} \bar{h}_1^\perp h_1] + B(y) \sin(3\phi - \phi_{S_2}) \\
&\times \mathcal{F}[\frac{4\hat{\mathbf{h}} \cdot \mathbf{p}_{1T}(\hat{\mathbf{h}} \cdot \mathbf{p}_{2T})^2 - 2\hat{\mathbf{h}} \cdot \mathbf{p}_{2T} \mathbf{p}_{1T} \cdot \mathbf{p}_{2T} - \hat{\mathbf{h}} \cdot \mathbf{p}_{1T} \mathbf{p}_{2T}^2}{2M_1 M_2^2} \bar{h}_1^\perp h_{1T}^\perp]] \} \\
&+ \dots,
\end{aligned} \tag{5}$$

where the notation \mathcal{F} is defined as

$$\begin{aligned}
\mathcal{F}[\omega \bar{f} g] &\equiv \sum_{a, \bar{a}} \int d\mathbf{p}_{1T} d\mathbf{p}_{2T} \delta^2(\mathbf{p}_{1T} + \mathbf{p}_{2T} - \mathbf{q}_T) \omega(\mathbf{p}_{1T}, \mathbf{p}_{2T}) \\
&\times \bar{f}^{\bar{a}}(x_1, \mathbf{p}_{1T}) g^a(x_2, \mathbf{p}_{2T}),
\end{aligned} \tag{6}$$

and

$$A(y) = \frac{1}{2} - y + y^2 \stackrel{\text{cm}}{=} \frac{1}{4}(1 + \cos^2 \theta), \quad B(y) = y(1 - y) \stackrel{\text{cm}}{=} \frac{1}{4} \sin^2 \theta. \tag{7}$$

The parton distribution functions (PDFs) which appear in the expression are transverse momentum dependent (TMD) parton distributions, whose factorization in SIDIS and Drell-Yan processes has been proved in Refs. [30,31,32,33], and holds in the regime $q_T^2 \ll M^2$, $p_i \simeq q_T$. Similar to the SIDIS process, the integration over \mathbf{q}_T directly leads to zero result for the last two terms in Eq. (5), so we have to define the weighted asymmetry

$$A_{UT}^{W(\phi,\phi_S)} = \frac{2 \int_0^{2\pi} d\phi W(\phi, \phi_S) [d\sigma^\uparrow - d\sigma^\downarrow]}{\int_0^{2\pi} d\phi [d\sigma^\uparrow + d\sigma^\downarrow]}. \quad (8)$$

With proper weight functions $W(\phi, \phi_S)$ which depend on the azimuthal angles ϕ and ϕ_S , we can distinguish the $\sin(\phi + \phi_S)$ and the $\sin(3\phi - \phi_S)$ asymmetries from the differential cross-section. In this study, we will plot the $\sin(\phi + \phi_S)$ and the $\sin(3\phi - \phi_S)$ weighted asymmetries, for they can give us the information on the transversity and pretzelosity we are interested in. Also we remind that a Monte Carlo simulation for the $\sin(\phi + \phi_S)$ asymmetry in πp^\uparrow Drell-Yan process has been given in [34].

3 Numerical calculation

We will consider the $\pi^-(\pi^+)p^\uparrow \rightarrow \mu^+\mu^-X$ process, where a valence $\bar{u}(\bar{d})$ quark from $\pi^-(\pi^+)$ and a $u(d)$ quark from p annihilate. Here we have ignored the contribution from sea quarks since we assume that the polarized effect from sea quarks is small. For the proton PDFs, we will use the results obtained in a light-cone quark spectator diquark model [35,26] with the relativistic Melosh-Wigner effect [36] of quark transversal motions taken into account. The TMDs we deduce from this model are applicable in the hadronic scale. To compare with the experimental observables which are usually measured at rather high energies, it is essential to evolve the parton distributions to the scale from an initial scale. However, here we calculate the azimuthal asymmetries which are the ratios of different parton distributions, so the effects of evolution are assumed to be small. In practice, we use this model to obtain the helicity and transversity distributions, which are reasonable to describe data related to helicity distributions in a number of processes [37] and transversity distributions related to the Collins asymmetry at HERMES [38]. This model is also successful in the prediction of the dihadron production asymmetry at COMPASS [39,40]. So it is worth trying to apply this model to the Drell-Yan kinematics at COMPASS. Besides this, we need the Boer-Mulders function for a pion [41,42], of which the knowledge is limited, and we will use the parametrization in Ref. [41], which was obtained in a quark spectator anti-quark model. The pion parton distributions we adopt were demonstrated [41] to give a good description on the $\cos 2\phi$ asymmetries measured in the unpolarized πN Drell-Yan process [43], where a large and increasing asymmetry was observed in the q_T region below 3 GeV, thus our model has been checked to be reasonable in this region. Another important feature we should remember is that this T -odd function has a different sign in the Drell-Yan process with that in the SIDIS process [18,20,44],

$$h_1^\perp|_{\text{DY}} = -h_1^\perp|_{\text{SIDIS}}. \quad (9)$$

In Ref. [41], the Boer-Mulders function is calculated for the SIDIS process, so we will make a sign change for our parametrization in our Letter. However, we should be careful that due to the chiral-odd nature of Boer-Mulders function, it always couples with another chiral-odd function for being probed. This makes it very difficult to obtain the information of this function, especially its sign. In the unpolarized Drell-Yan process, the Boer-Mulders function couples with itself, therefore it is impossible to determine its sign. In the SIDIS process, the Boer-Mulders function is combined with the Collins function, the extraction [45] of which also relies on the azimuthal asymmetry of hadron production in e^+e^- annihilation process. Also we will stress that unlike many other calculations, we do not make the ansatz that the transverse momentum dependence of the TMDs has a pure Gaussian form, but just deduce it from the model. That is, we evaluate the integration over the parton transverse momenta numerically. The experiment we consider is for COMPASS, where the kinematics we will use are [46]

$$\begin{aligned} \sqrt{s} &= 18.9 \text{ GeV}, \quad 0.1 < x_1 < 1, \quad 0.05 < x_2 < 0.5, \\ 4 &\leq M \leq 8.5 \text{ GeV}, \quad 0 \leq q_T \leq 4 \text{ GeV} \text{ (if } q_T \text{ is integrated)}. \end{aligned}$$

We will investigate the x_F, M and q_T dependence of the asymmetries. The integration range can be determined as follows.

- For the x_F/M dependence, given a fixed x_F/M , the range for M/x_F is determined by Eq. (4) so that $x_{1,2}^{\min} < x_{1,2}(x_F, M) < x_{1,2}^{\max}$.
- For the q_T dependence, the range for M is $4 \leq M \leq 8.5 \text{ GeV}$, and the range for x_F is determined by Eq. (4) so that $x_{1,2}^{\min} < x_{1,2}(x_F, M) < x_{1,2}^{\max}$.

In Figs. 1 and Fig. 2 (thick curves), we plot the $\sin(\phi + \phi_S)$ asymmetry and the $\sin(3\phi - \phi_S)$ asymmetry in the πp^\uparrow Drell-Yan at COMPASS, respectively. We can clearly see from the two figures that the asymmetries for the $\pi^- p^\uparrow$ process are much larger than those for the $\pi^+ p^\uparrow$ process, because that the former process is dominated by u quark while the latter is dominated by d quark. COMPASS will conduct a $\pi^- p^\uparrow$ plan in the near future, however, we will also give the prediction on the $\pi^+ p^\uparrow$ process as a supplement, and expect future experiments could direct this measurement to give us more information on the d quark distributions.

From Fig. 1, we find that similar to that in the SIDIS process, the $\sin(\phi + \phi_S)$ asymmetry is also significant in the Drell-Yan process, and the magnitude of the asymmetry reaches up to several percent. We can make a comparison with the results from Ref. [47], where a q_T dependence of the $\sin(\phi + \phi_S)$ asymmetry was investigated. Below 2 GeV, our two results seem to be consistent, but above 2 GeV, our result rises quickly and give a much larger asymmetry than that obtained in Ref. [47]. This needs further studies and a check by experi-

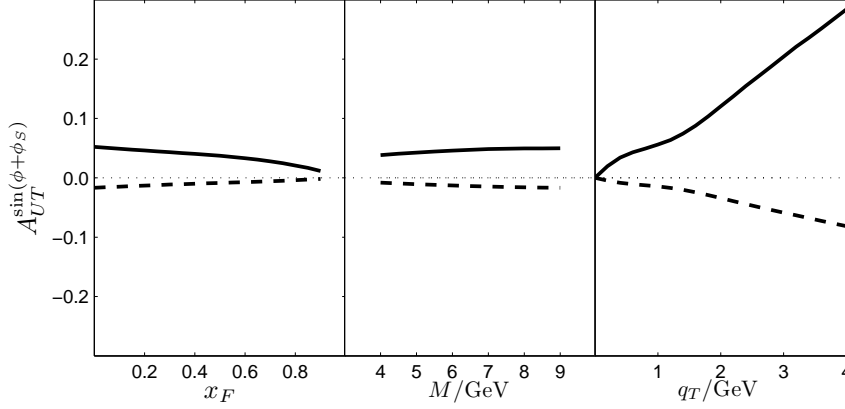


Fig. 1. The $\sin(\phi + \phi_S)$ asymmetries for $\pi^\pm p^\uparrow \rightarrow \mu^+ \mu^- X$ process at COMPASS. Solid and dashed curves are the results for π^- and π^+ productions, respectively.

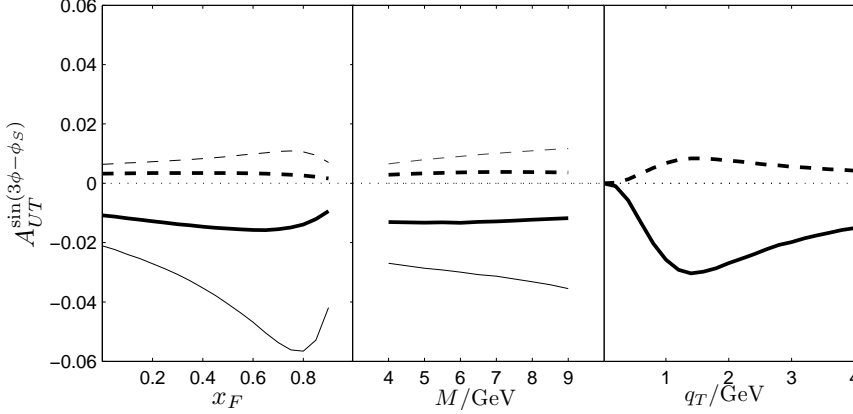


Fig. 2. Similar to Fig. 1, but for the $\sin(3\phi - \phi_S)$ asymmetries. The thin curves are calculated with a cut $1.0 \leq q_T \leq 2.0$ GeV.

ments. As to the $\sin(3\phi - \phi_S)$ asymmetry, however, we are not fortunate that it is not so large, but just around 1 – 2%, also similar to that shown in the SIDIS process [26]. In order to enhance the asymmetry, it has been suggested in Ref. [26] to make a cut on $P_{h\perp}$ by selecting the large $P_{h\perp}$ events. But there we faced a dilemma that $P_{h\perp}$ cannot be too large to spoil the TMD factorization, which only holds at the regime $P_{h\perp} \ll Q^2$. Here we will adopt the same approach to try to enhance the asymmetry in Drell-Yan process, i.e., we will make a cut on q_T . From the third subplot in Fig. 2, we find that the asymmetry is larger in the medium q_T region. So we choose the cut $1.0 \leq q_T \leq 2.0$ GeV, and this kinematics region on q_T also satisfies the condition $q_T^2 \ll M^2$, thus the TMD factorization is still valid. Without changing other kinematics and just integrating q_T from 1.0 GeV to 2.0 GeV, we recalculate the $\sin(3\phi - \phi_S)$ asymmetry, and the result is shown in Fig. 2 (thin curves). As we expect, the magnitude of the asymmetries is indeed enhanced by about two times after we make a cut on q_T . Although we may have a loss on the data, we hope that it would be helpful to measure this asymmetry from experiments. Here we em-

phasize that the weighting functions we choose depend only on ϕ and ϕ_S , but not on the transverse momenta of the dilepton. Meanwhile, we perform the integration over the parton transverse momenta numerically, therefore we do not need to introduce the transverse moments of the TMDs in our calculation.

In the SIDIS process, if we want to extract transversity or pretzelosity, we should know the information about the Collins fragmentation function. In the Drell-Yan process, transversity or pretzelosity also needs a chiral-odd partner, e.g., the Boer-Mulders function, of which the knowledge is limited, especially for a pion beam. However, the Boer-Mulders function of the pion can be accessed through unpolarized pion nucleon Drell-Yan process at COMPASS [48]. Furthermore, all the TMDs we used in our Letter are from the same model, therefore they are consistent with each other. Thus the relevant experiment will give constraints on the transversity/pretzelosity and Boer-Mulders functions, though a complete knowledge on the TMDs must rely on more experiments.

4 Conclusion

We have presented the $\sin(\phi + \phi_S)$ and $\sin(3\phi - \phi_S)$ single spin asymmetries for the $\pi^\pm p^\uparrow \rightarrow \mu^+ \mu^- X$ process at COMPASS. For the $\pi^- p^\uparrow$ process, the $\sin(\phi + \phi_S)$ asymmetry is several percent and can be measured through the experiment. However, the $\sin(3\phi - \phi_S)$ asymmetry is small, which is similar to the case in the SIDIS process, thus there is some difficulty in measuring it. We adopt a cut on q_T as used before to solve the similar difficulty in SIDIS process, and our attempt succeeds in enhancing the asymmetry. For the $\pi^+ p^\uparrow$ process, we get an expected smaller result due to the different quark dominance. Our purpose is to study transversity and pretzelosity of the proton through SSAs in Drell-Yan process, for this we apply the Boer-Mulders effect of a pion beam, which will be available at COMPASS. Therefore our predictions on the $\sin(\phi + \phi_S)$ and $\sin(3\phi - \phi_S)$ asymmetries in Drell-Yan process rely on the knowledge of the Boer-Mulders function. Nevertheless, our model prediction can give constraints on the relevant physical quantities, and we expect more experiment data to provide us more knowledge on the spin structure of the nucleon, especially, the chiral-odd structure of the transversely polarized nucleon.

Acknowledgement

This work is partially supported by National Natural Science Foundation of China (Nos. 10905059, 11005018, 11021092, 10975003, 11035003) and by

FONDECYT (Chile) under project No. 11090085.

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